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URANIUM-LIQUID ARGON CALORIMETRY: PRELIMINARY RESULTS FROM THE DO TESTS*

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Uranium-Liquid Argon Calorimetry: Preliminary Results from the D0 Tests

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Abstract

The motivations for using uranium and liquid argon in sampling calorimetry are reviewed and the pros and cons of the technique are discussed. Preliminary results of the D0 uranium-liquid argon test program are presented.

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Introduction

Recently interest has been high in the possiblities for uranium-liquid argon calorimetry as the technique of choice for large detectors that are being planned for the Fermilab Collider, LEP, SLC and HERA. Much of this interest has been generated by the pioneering work of C. Fabian et ali whose prototype calorimeter achieved significantly better hadronic energy resolutions and more nearly equal electron and hadron response using uranium than had been achieved using Fe or other materials. These potential advantages coupled with the higher density (approaching 8 gm/cm£ in real uranium plate calorimeters) has stimulated extensive R&D efforts intended to investigate further the properties of uranium-liquid argon calorimeters.

Uranium is under consideration for calorimeters not only because of its high density but also because of the hadron induced fission that takes place in the uranium during the shower process. Some of the fission products (neutrons, gammas and electrons) leave the uranium plates and produce signals in the liquid argon thereby increasing the visible hadronic signal and compensating for what otherwise would be the hidden energy lost in breaking up the nuclei. The better resolution of uranium calorimeters is thought to be partially due to these phenomena.

In addition to this effect which increases the size of the hadronic signal in a uranium-liquid argon calorimeter, there are several effects[2,3,4] which decrease the signals due to electron showers in high Z calorimeters. The first of these effects is due to the differences in critical energies of the uranium (6.0 MeV) and argon (30.5 MeV). The critical energy of a material is by definition the energy loss per radiation length due to collisions of electrons and positrons in that material. At the boundary between materials with very different critical energies such as uranium and argon, the collision losses will increase abruptly as the shower enters the argon, causing a loss of electrons from the shower. This will tend to lower the signal due to that shower. In an Fe-liquid argon calorimeter the difference in critical energies is not so great and the decrease of the electron shower signal will not be so great. A second effect that tends to decrease the electron signal in a uranium-liquid argon calorimeter relative to that in a Fe-liquid argon calorimeter is the increased track length in the uranium relative to the argon due to multiple scattering in the uranium. Finally a third effect which can decrease the electron pulse height in any calorimeter is the saturation of the active medium by low energy electrons in the later generations of an electromagnetic shower.

These effects, taken together, tend to raise the pulse height of hadronic showers and decrease the pulse height of electromagnetic showers in a uranium-liquid argon calorimeter relative to those observed in an Fe-liquid argon calorimeter. The net effect is in the direction of making the response of a uranium-liquid argon calorimeter to electromagnetic and hadronic showers more nearly equal than that of an Fe calorimeter. This equality of electromagnetic and hadronic signals has been advanced as the reason for the better hadronic resolution of uranium calorimeters. The degradation of the hadronic resolution due to variations in the relative size of the the em and hadronic components of the shower will be minimized if the calorimeter response to electromagnetic and hadronic showers is equal. Therefore the measurement of the ratio of the electromagnetic to hadronic response of a given calorimeter configuration is a prime objective of any calorimetry test program.

The suppression of the response of a high Z calorimeter to electromagnetic showers can be observed in the relative response of the calorimeter to electrons and muons. The observed electron signals in the calorimeter can be used to determine the apparent energy of the observed muon signal on the electron scale. From that apparent energy, the muon energy that is deposited in the liquid argon can be calculated using

$$S = \frac{(x \cdot dE/dx)_A}{(x \cdot dE/dx)_A + (x \cdot dE/dx)_U} = \text{fraction of shower energy visible in the liquid argon} \qquad (1)$$

When the muon energy deposit calculated in this way is compared with the actual muon energy deposit measured directly using absolute amplifier gains or other measurements of dE/dx of muons in liquid argon, it is normally found to be considerably larger. The fact that this ratio (known as the 'μ/e' ratio) is greater than one is a manifestation of the 'transition effects'. Their suppression of the electron response of the calorimeter makes the apparent muon energy appear to be larger than it is in reality.

There are many contributions to the energy resolution of a uranium liquid argon calorimeter other than the ordinary sampling fluctuations due to hidden energy in the plate structure or the fluctuations in hadronic response due to an e/π ratio different from one. In general the energy resolution of such a device may be written as the sum in quadrature of three supposedly independent terms:

$$\sigma = \sqrt{A^2E^2 + (B\sqrt{E})^2 + (C)^2} \qquad (2)$$

There are several effects which contribute to each term. The A term which is proportional to the energy includes contributions from errors in the gain determination of each channel, contributions due to inductive or capacitative coupling of one section or channel of the calorimeter to another and variations in plate or gap thickness in a real calorimeter. Spread in beam momentum also contributes to this term. The B term which is proportional to the square root of the energy contains the sampling fluctuation contributions to the resolution. These include both the intrinsic shower fluctuations and fluctuations in energy deposit for a given shower between visible energy in the active medium and the hidden energy in the plates. Finally the C or constant term includes energy independent contributions to the resolution such as coherent and incoherent electronic noise, uranium radioactivity noise and drifts in electronic pedestals. Other effects such as the fluctuations between the electromagnetic and hadronic components of a hadronic shower in a calorimeter in which e/π is not equal to one or the leakage of shower energy out of a calorimeter will contribute to the resolution in a more complicated way that cannot be represented by a simple contribution to a single term of (2). Each of these contributions to the resolution function will occur in different amounts for a particular calorimeter and must be determined by suitable testing of that calorimeter.

Preliminary Results from the D0 Liquid Argon-Uranium Tests

Recently several institutions collaborating on the D0 experiment[5], E740, at Fermilab have conducted a series of tests to measure the response of a uranium-liquid argon test calorimeter to high energy hadrons and electrons. These tests were performed in the NW test beam at Fermilab at 10,15,25,50,100 and 150 GeV/c with electron and hadron data taken at each momentum. The data presented in this paper is that obtained using the thinnest uranium plate configuration that was tested in the course of this program. The preliminary results presented in this paper represent the state of the analysis of these data at the time of this talk (August,1985) and will be superseded by a more complete analysis to be published later. The liquid argon test cryostat and the uranium plate configuration that was used to obtain these data is shown in Fig. 1 and tabulated in Table I below:

Table I
D0 "Thin" Plate Uranium-Liquid Argon
Test Calorimeter Configuration
(Argon Gap Thickness=1.6 mm)

Section	Plate Thickness	#Cells	$\#X_0$	λ_a	L(cm)	Sampling Fraction
EM-1	2 mm U	4	2.6			
EM-2	2 mm U	4	2.6			
EM-3	2 mm U	8	5.3	0.8	20.4	.127
EM-4	2 mm U	14	9.2			
FH-1	4 mm U	24	-	1.1		
FH-2	4 mm U	64	-	2.8	99.0	.072
FH-3	4 mm U	24	-	1.1		
L-1	19 mm Cu	12	-	1.6		
L-2	19 mm Cu	12	-	1.6	57.0	.026
Totals		166	19.7	9.0	176.0	

The configuration of a cell (plate-argon gap-G10 readout board-argon gap) is shown in Fig. 2a. In Fig. 2b the 48 pad transverse readout structure of the G-10 readout boards is shown. The two pad sizes that were used were 2"x2" and 4"x4". The nine longitudinal readout sections listed in Table I were further subdivided by bringing out and digitizing separately the sum of every other gap in each of the nine sections. This allowed the major effects of doubling the plate thickness to be measured by observing the resolution achieved using signal from the sum of half the gaps. (Measurements of a test calorimeter in which the plate thickness was actually doubled were made to check that there were no subtle effects on the 'e/π' ratio or the hadronic resolution due to the presence of the extraneous argon gaps in the half the gap sum described above. No significant differences were detected between the results obtained summing every other gap and the double plate thickness test.)

For the transverse and longitudinal readout configuration described in Table I a total of 696 channels of electronics were required. The electronics is shown schematically in Fig. 3a. As indicated, it consisted of an charge sensitive preamplifier stages which used Toshiba 2SK147 FETs followed by a baseline subtractor stage. The output of the baseline

subtractor stage was digitized by a LeCroy 2280 ADC system. The test calorimeter was operated with the uranium plates at negative high voltage in the configuration shown in Fig. 3b. Each uranium plate had a 100 nf buffering or blocking capacitor and a 50-100 ohm protection resistor in series to the high voltage. Both the blocking capacitor and the protection resistor were inside the test cryostat in the liquid argon.

The test calorimeter was positioned in a 'bathtub' inside the cryostat which was filled with liquid argon by condensation from a nitrogen cooling coil. The cryostat was maintained at 10 psi gauge during the cool down and fill process by regulating the liquid nitrogen flow to the cooling coil. This overpressure was maintained in order to minimize contamination of the 1000 liter liquid argon inventory by oxygen. The argon used in the test was obtained as bottles of liquid from commercial sources, allowed to boil and then recondense in the cryostat. Each bottle of liquid argon was checked using an alpha source in a small test cell to insure purity. Typical results of these measurements are shown in Fig. 4a in comparison with the published results of Willis and Radeka[7]. The purity of the liquid argon inventory in the cryostat was monitored by a similar alpha source mounted in the bathtub and by a oxygen monitoring device which sampled the boil off argon gas from the cryostat volume. The purity of the liquid argon inventory achieved with these precautions is indicated by the good quality of the high voltage plateau curves shown in Fig 4b. These were obtained with 50 GeV/c electrons and hadrons. For the majority of the data discussed in this paper an operating point of 1500 volts was used. The oxygen contamination monitor generally recorded 1-2 ppm of oxygen and the bathtub alpha source gave pulse heights quite similar to the test cell alpha source during the period of these tests.

The response of the test calorimeter to electrons, hadrons and muons is shown in Fig. 5a, b and c. Using the pulser calibration of the electronics and a 52.4 eV deposit per observed electron for argon, the deposited energy in the calorimeter corresponding to the average muon pulse height is calculated to be 89 MeV. This is to be compared to the expected energy deposit[8] of approximately 100 MeV for a minimum ionizing particle in liquid argon. However, if the observed pulse height of 150 GeV electrons is used along with the observed pulse height of muons in the electromagnetic section to determine the apparent energy deposit of the muons (using a sampling fraction of 12.6% in the electromagnetic section), then a μ/e ratio of 1.9 ± 0.3 is obtained showing the suppression of the electron signal by the various effects mentioned in the introduction.

The linearity of the calorimeter for electrons and hadrons is shown in Fig. 6. The electron signal is defined for the linearity plot as the sum of the electromagnetic sections plus the first hadronic section of the calorimeter while the hadron signal is formed from the sum of all sections. In all cases when the electron and hadron pulse heights are formed from the signals observed in the different sections of the calorimeter, formula (1) is used to correct for the differing percentages of visible energy deposit in the different sections. As can be seen in Fig. 6, the electron pulse heights are larger than the hadronic pulse heights at all energies.

The resolutions for hadrons and electrons have been extracted from the raw data with the electron signals formed as indicated above from the sum of the em sections and the first fine hadronic section of the test calorimeter. The hadronic signals are formed from the sum of all sections of the calorimeter. These data have been corrected for amplifier gain differences, beam momentum on an event by event basis, and for the ringing of the signals due to inductive coupling between channels. In addition, all channels which were within 1.5 σ of their average pedestal values were deleted from the energy sum (the average noise per channel was approximately 6 MeV for the EM sections and approximately 12 MeV per channel for the hadronic sections). With these corrections and cuts the variations of the electron and hadron resolution as a function of $1/\sqrt{E}$ are shown in Figs. 7a and b. The approximate fits of $\sigma/E=\sqrt{A^2+(B/\sqrt{E})^2+(C/E)^2}$ are shown superimposed on the data. At this stage of analysis the coherent electronic noise dominates the resolution at low energies. At high energies the resolution is probably influenced by factors such as the uniformity of plate and gap thickness that we were able to achieve in the construction of the test calorimeter. We have also determined the resolution obtained by summing the signals from every other gap. The ratio of this resolution for electrons and hadrons to that determined from the sum of all gaps is shown in Fig. 7c. The dotted line at the $\sqrt{2}$ level is the ratio which would be expected if the resolutions were dominated by sampling fluctuations. While the electron resolution ratio is near that level, the hadronic resolution ratio is appreciably below that level indicating the presence of other contributions to the resolution.

The ratio of the electron to hadron pulse heights has been determined from these data with all of the above mentioned cuts and corrections except for the 1.5 σ noise cut. Formula (1) has been used to add signals from various parts of the calorimeter. The 1.5 σ cut was not used in this determination so that any effects on the absolute pulse heights of electrons and hadrons due to differences in the number of channels excluded for

electrons and hadrons would be minimized. The values at the different energies for the most part lie between 1.0 and 1.1 with the definition of the electron pulse height used in the determination. There is little or no variation of this 'e/π' ratio with energy between 10 and 150 GeV/c.

Several other measurements were made with this test calorimeter. A determination of the uranium radioactivity noise was made with both negative and positive high voltage on the uranium plates by measuring the broadening of the pedestal as a function of high voltage. With negative high voltage on the uranium plates, we find that the uranium radioactive noise can be represented by

$$\sigma_U = 0.12 \sqrt{A\tau}/s \quad (\text{MeV})$$

where s is the sampling fraction for the particular section of the detector in which the uranium noise is observed, A is the area in square meters of the readout pads which are being summed and τ is the sampling time of the digitizing system in nanoseconds. Reversing the high voltage polarity reduces the uranium noise by 25%.

Finally we have tried adding photosensitive dopants[9] to the liquid argon in attempt to modify the 'e/π' ratio. We first added isobutylene (C_4H_8) at the 27 ppm level. While the electron and hadron pulse heights and resolutions at 25 and 100 GeV/c did not change, the pulse height of the monitor alpha source increased by over 50% and the maximum voltage at which the plate array could be operated without sparking decreased from 2400 V to approximately 1300 V. The same general behavior was observed with allene(C_3H_4). The increase of the alpha particle pulse height and simultaneous lack of change of the hadronic pulse height is taken as evidence that the component of hadronic showers due to heavily ionizing particles is negligible.

Conclusions

Uranium-liquid argon calorimetry has many attractive features for hadronic calorimetry. These include the high density relative to other types of calorimetry and the approximate equality ($e/\pi \approx 1.0 \rightarrow 1.1$) of electron and hadron signals as measured by the D0 collaboration. The resolutions for hadrons in the 10 to 150 GeV/c range are somewhat better than those obtained by comparable Fe-liquid argon calorimetry. This is due at least partially to the near equality of the response to electrons and hadrons. This equality minimizes the contribution to the resolution due to

fluctuations between the electromagnetic and hadronic components of the hadronic showers. Noise due to uranium radioactivity has been found to contribute $\sigma=0.12\sqrt{A\tau}/s$ (MeV) to the energy resolution where A is the area of the plate in m^2, τ is the sampling time of the digitizing electronics in nanoseconds and s is the sampling fraction of the calorimeter. If the calorimeter is operated with positive high voltage on the uranium plates this noise is found to be 25% less. Finally, the addition of photosensitive dopants to the liquid argon is found to have little effect on the electron or hadron showers but causes major changes in the pulse height of an alpha source monitor. This observation leads to the conclusion that heavily ionizing particles do not constitute a large component of hadronic showers in uranium-liquid argon calorimeters.

Acknowledgments

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9. Following a suggestion by D. Anderson.

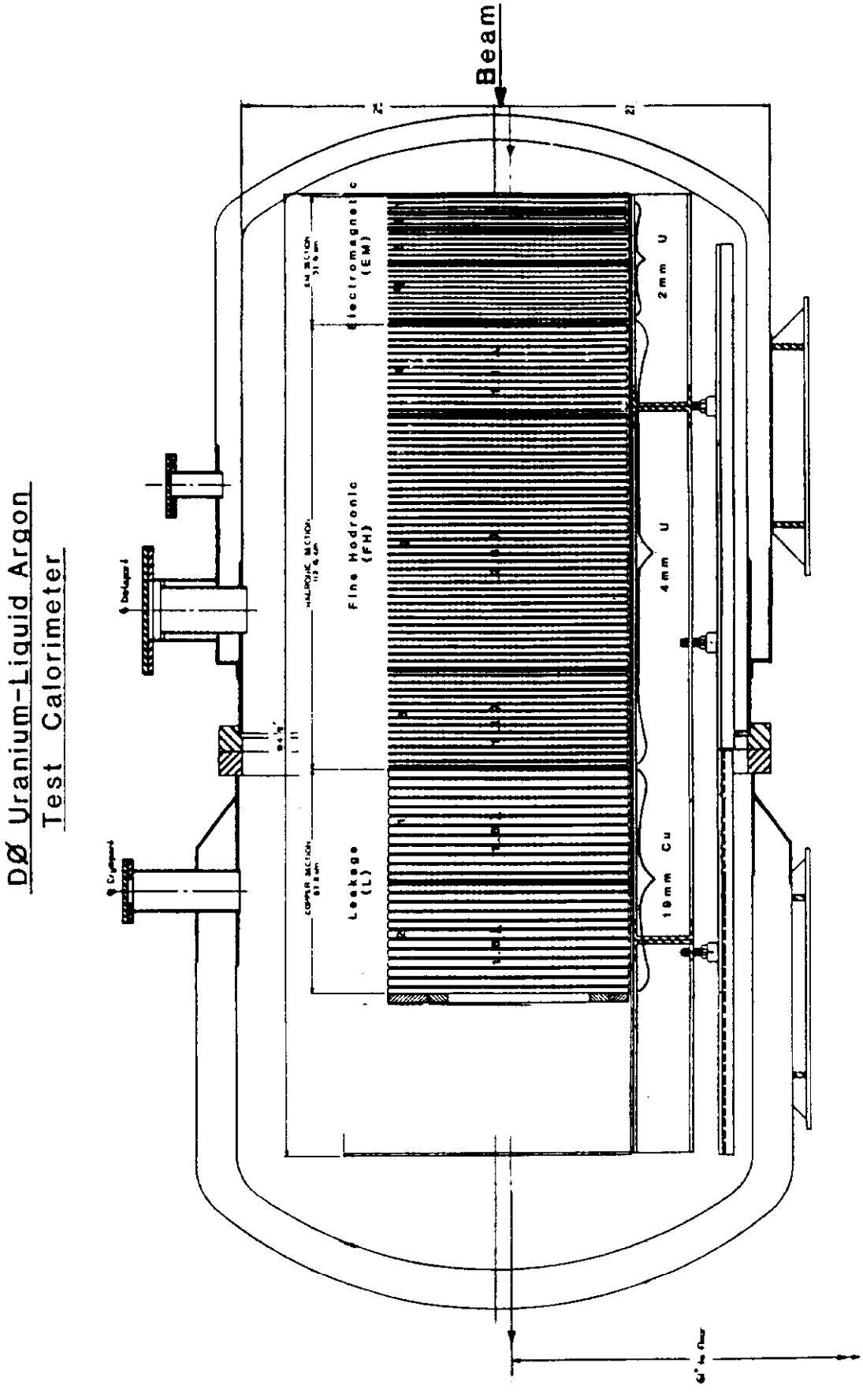


Fig. 1: DØ test calorimeter and cryostat

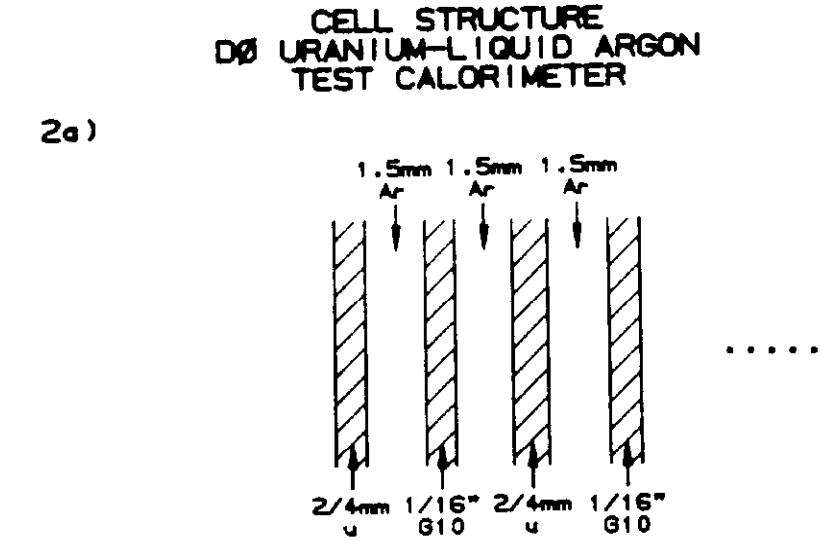


Fig. 2a: Cell structure for "thin" uranium plate assembly used in DØ tests.

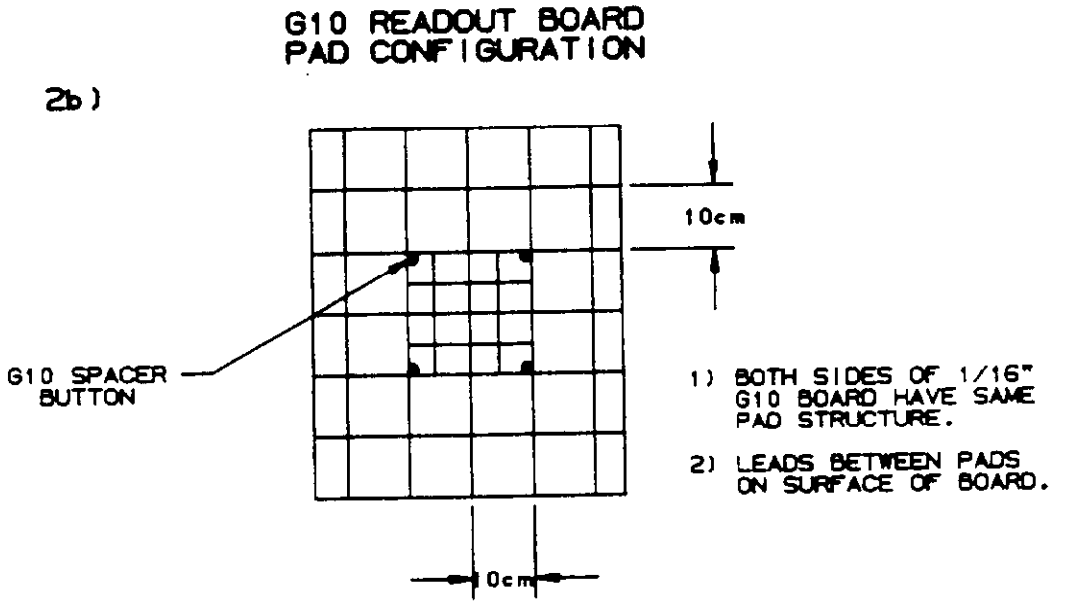
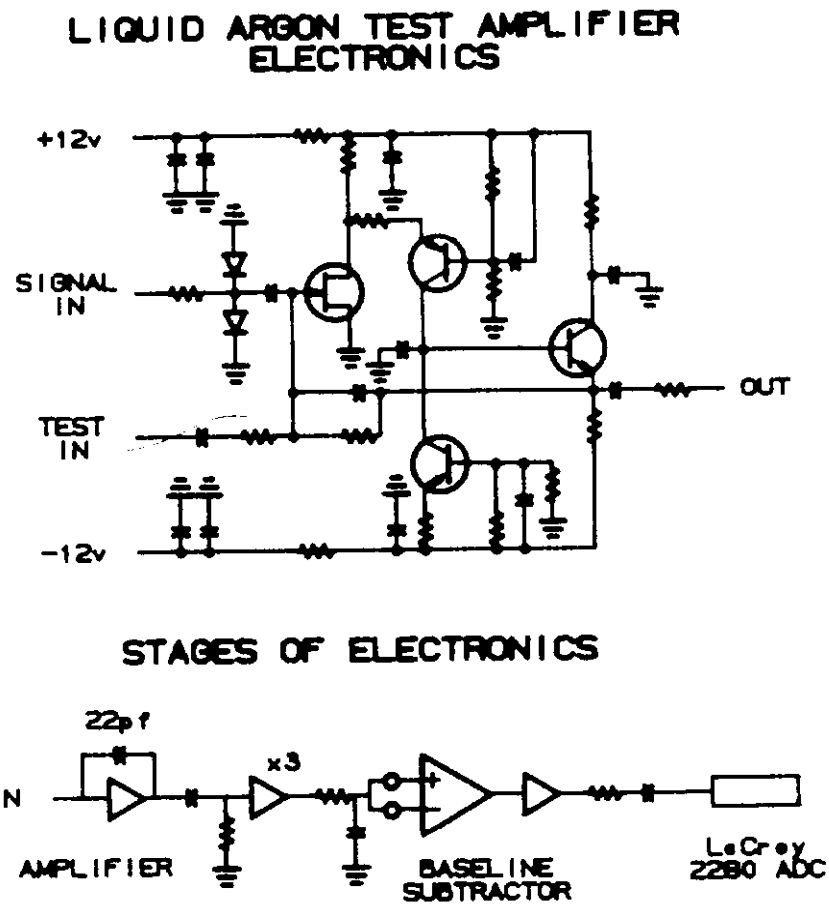


Fig. 2b: G-10 readout board pad configuration used in DØ tests. Both sides of the 1/16" G-10 readout boards have identical pad structures.

3a)



3b)

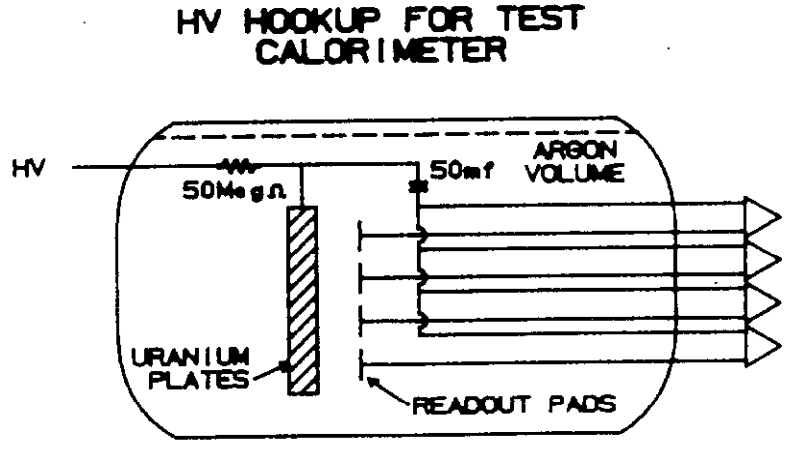


Fig. 3: a) Schematic of the DØ liquid argon amplifier and the general configuration of the integrating amplifier-baseline subtractor-ADC system, b) configuration of the high voltage hookup of the uranium plates for the DØ calorimetry tests.

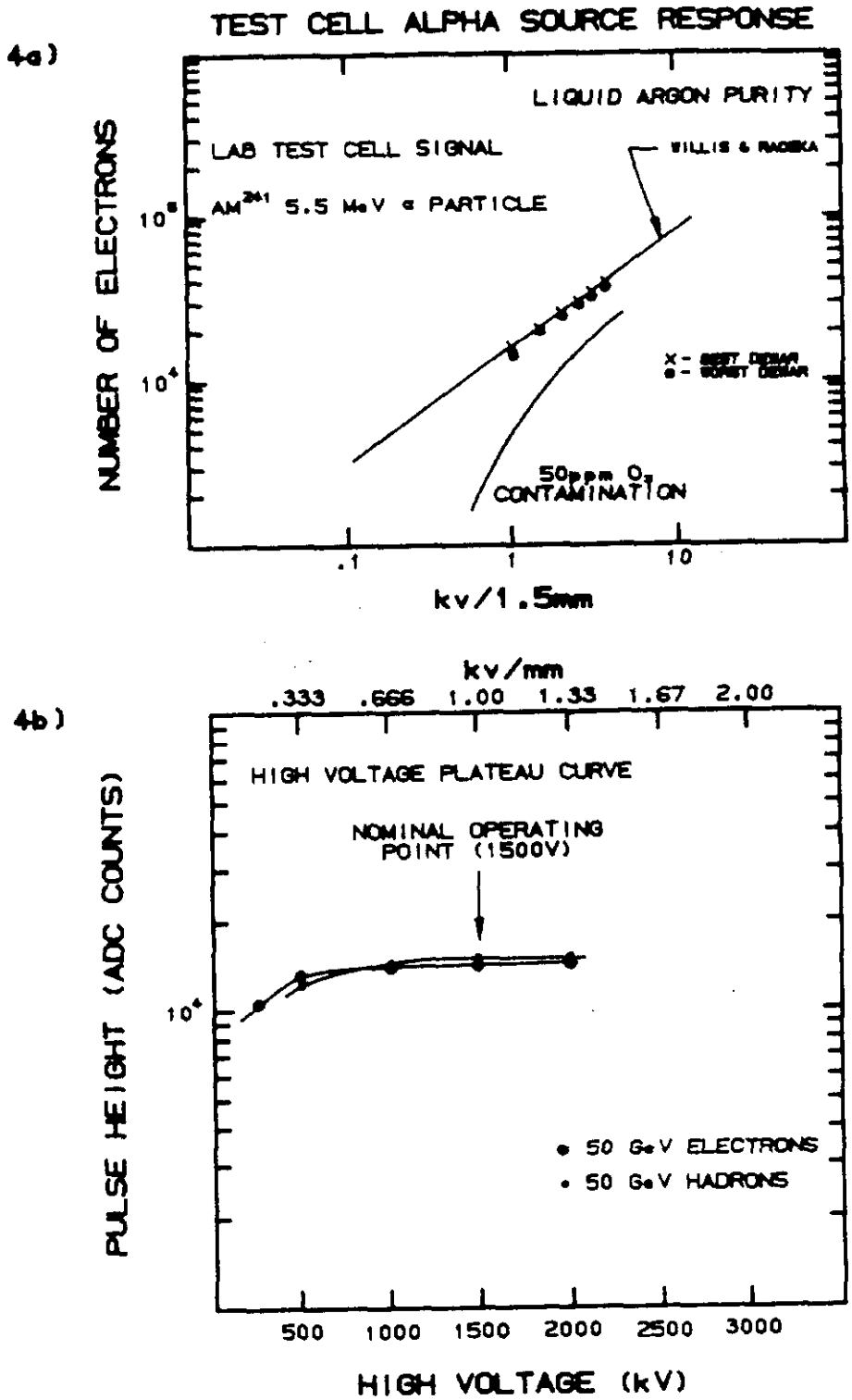
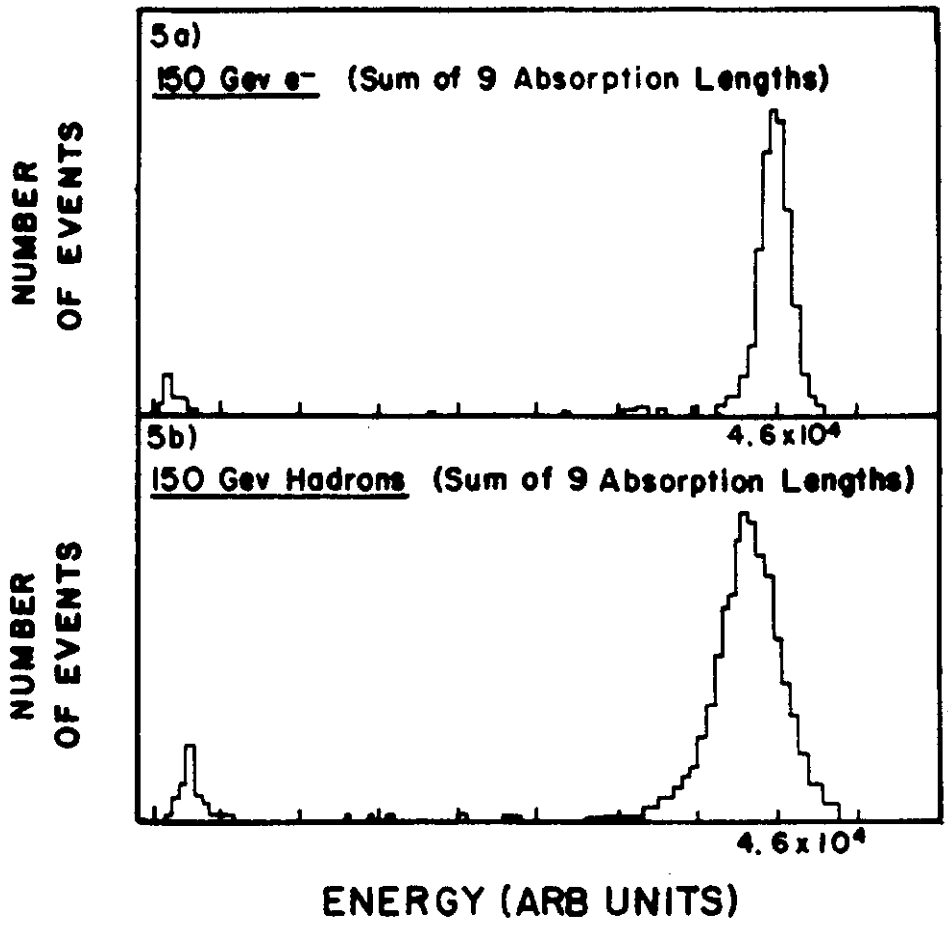


Fig. 4: a) Variation of the test cell alpha source signal as a function of voltage for several bottles of commercial grade liquid argon used in the DØ tests, b) high voltage plateau curves for 50 GeV hadrons and electrons.



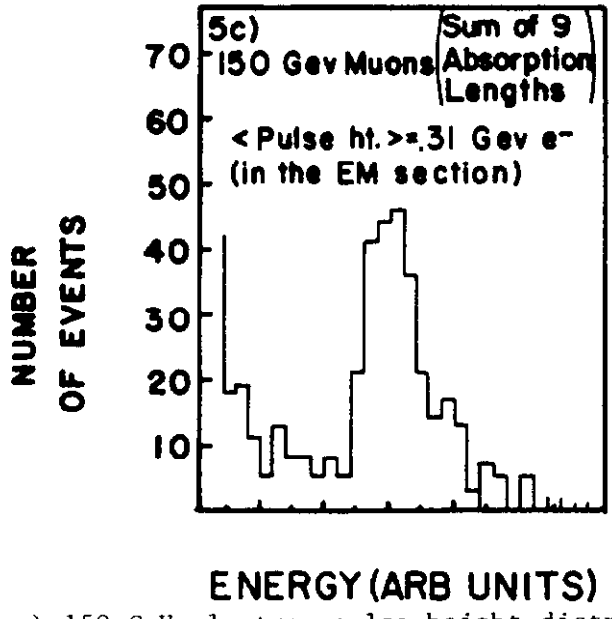


Fig. 5: a) 150 GeV electron pulse height distribution,
b) 150 GeV hadron pulse height distribution,
c) 150 GeV muon pulse height distribution

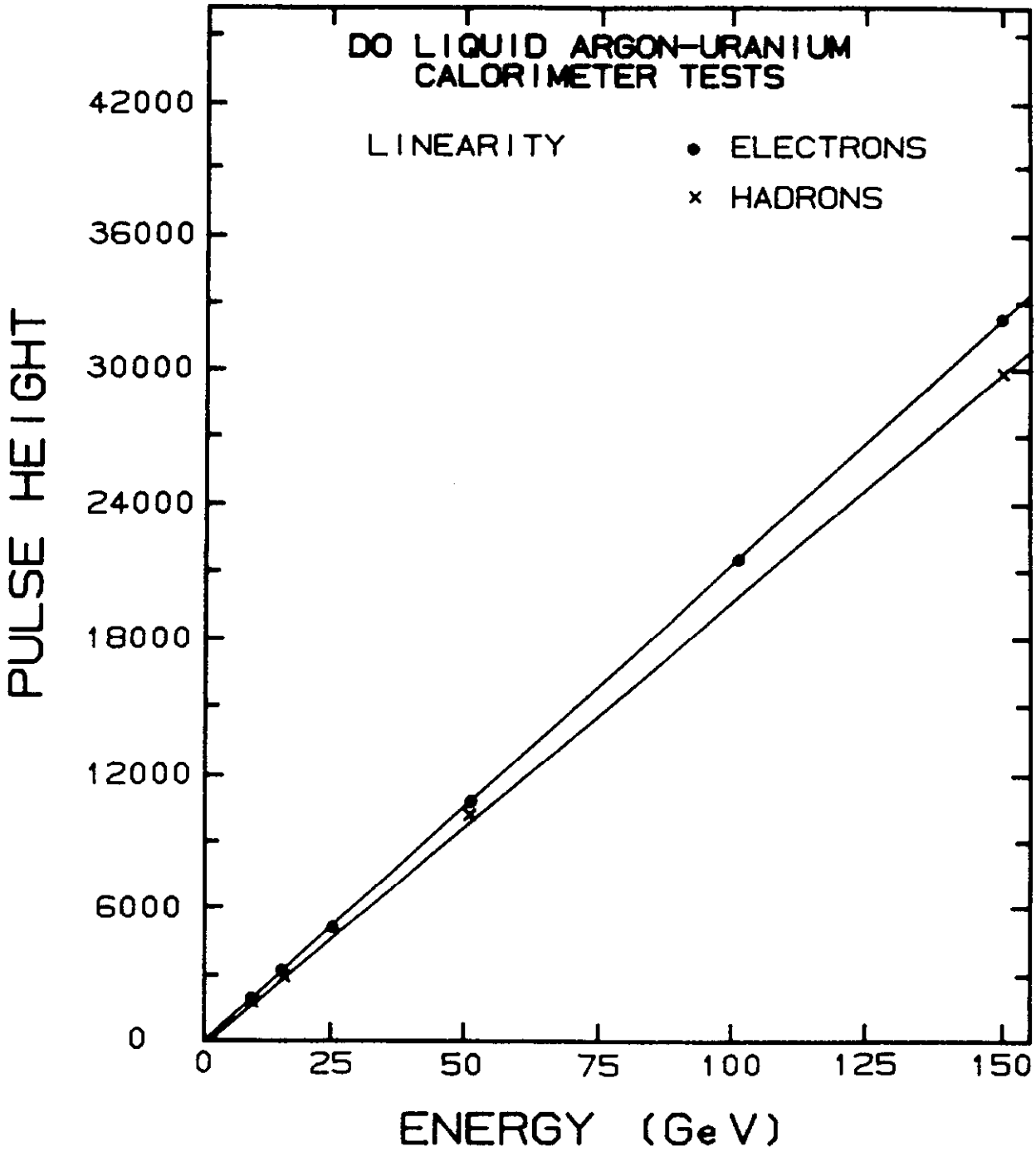


Figure 6: Linearity of the DØ test calorimeter for electrons and hadrons.

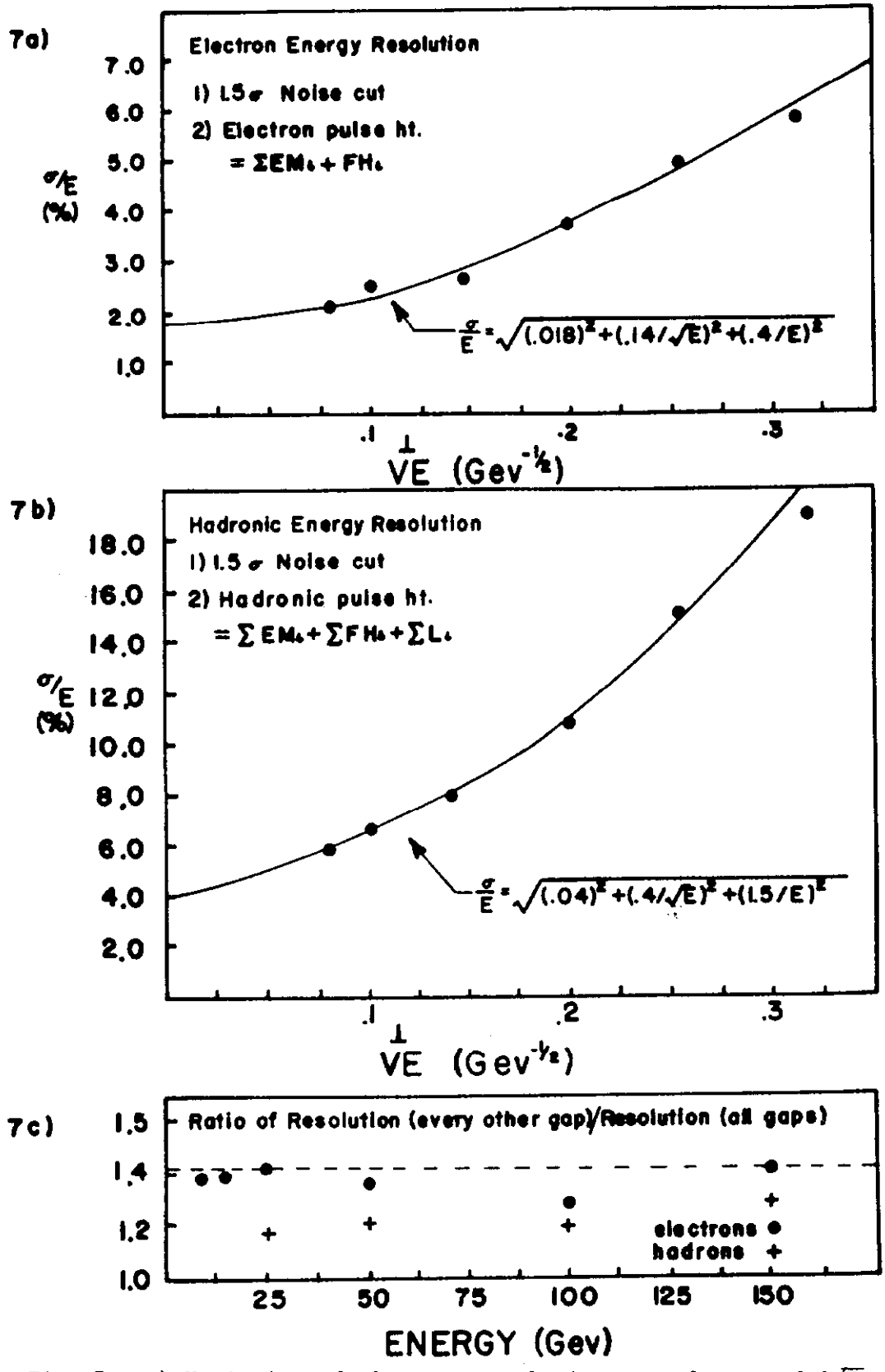


Fig. 7: a) Variation of electron resolution as a factor of $1/\sqrt{E}$, b) variation of the hadron resolution as a function of $1/\sqrt{E}$, c) ratio of the resolution obtained from summing every other gap to that obtained from summing all gaps.